Precise Orbit Determination for Low-Earth Orbiting Satellites using GPS Data: Recent Advances

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BIOGRAPHIES

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ABSTRACT

In this paper, we describe some recent advances in GPS-based precise orbit determination for low-Earth orbiting satellites. We will focus mainly on the Topex/Poseidon (T/P) satellite, which was launched in 1992. The T/P satellite carries a 6-channel Motorola Monarch GPS demonstration receiver (GPSDR), which is capable of collecting dual frequency (L1/L2) data when the GPS anti-spoofing (AS) function is inactive. Data from the first two post-launch years have been used to routinely compute T/P orbits with a radial accuracy at the 2 cm RMS level. Since the routine activation of GPS AS, in 1994, the GPSDR has collected GPS data mainly at the L1 frequency. Although the corresponding single frequency orbits (which have been routinely produced with radial accuracies at the 4-6 cm RMS level) are less accurate than the dual frequency orbits, they are available on a next-day basis and have been used to support a variety of emerging operational oceanographic applications. Most notable in this last category was the monitoring of the 1997-98 El Niño event. In the last year, several new modifications to the solution strategy have been investigated. With these enhancements, our results indicate that the next-day T/P GPS (AS) orbits can be computed with a radial accuracy of better than 3 cm RMS. Such orbit quality is unprecedented for single frequency data, and approaches the quality of the official precise orbit ephemeris (computed using

data from Satellite Laser Ranging (SLR) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)). We also discuss the Geosat Follow-On (GFO) mission, an altimetric satellite launched in February, 1998. The GFO satellite carries advanced 8-channel codeless TurboRogue GPS receivers, capable of collecting dual frequency (L1/L2) GPS data in the presence of AS. These data are expected to support 2-3 cm radial RMS accuracy for the GFO orbit, independent of AS status.

INTRODUCTION

Today, the importance of monitoring and modeling our oceans is very well recognized. For instance, changes in weather conditions associated with El Niño Southern Oscillation (ENSO) events have been well publicized and have scientific and societal significance. Information about the ocean height allows us to make direct inferences about the ocean circulation patterns and also about the likely consequences for atmospheric conditions. Satellite altimetry missions provide a convenient and reliable source for high-quality data on the sea-surface height. Radar altimeters based on current technologies have open-ocean range accuracies at the few cm level. To realize this accuracy in terms of sea-surface height, the concept relies heavily on high-quality precision orbit determination (POD). Over the last few years GPS-based POD has emerged as a powerful approach for generating high-quality satellite orbit solutions.

The Topex/Poseidon (T/P) mission was the first altimetric satellite specifically designed for monitoring ocean circulation patterns at scales bearing significantly on climate change. It is a joint venture between the French space agency (CNES) and the US space agency (NASA). The T/P satellite was launched in August, 1992, and orbits at an altitude of 1336 km. It is the first altimetric satellite to carry a GPS receiver. The so-called GPS Demonstration Receiver (or GPSDR) is an experimental 6-channel receiver, whose primary purpose was to test the validity of using GPS-based data for POD. Until January, 1994, the GPSDR successfully tracked the GPS satellites gathering dual-frequency (L1/L2) data. Based on these dual-frequency data, post-processed orbits with radial accuracies better than 2 cm RMS were produced [cf., Bertiger et al. 1994; Thornton et al., 1997]. However, on January 31, 1994, the Anti-Spoofing (AS) option was switched on in the GPS signal. With AS switched on, the known P-code in the GPS signal is replaced with the encrypted Y-code. Owing to the design of this experimental receiver, the implications for the GPSDR were that it could no longer track the L2 signal. Consequently, GPS-based POD efforts for T/P have relied on single-frequency data since January 1994. The largest drawback with using only single-frequency (L1) data is that the dispersive ionosphere delay experienced by the L1 signal can no longer be removed by calibration with the L2 signal, and must be modeled (typically using climatological ionosphere models). The systematic errors stemming from residual unmodeled ionosphere delay also encumber efforts to remove errors associated with unmodeled or mismodeled forces, such as the solar radiation pressure. (Errors associated with these forces can be partially removed by using a so-called reduced dynamic filtering strategy.) Until June 1997, JPL's next-day, single-frequency, GPS-based T/P orbits were routinely produced with radial accuracies at the 4-6 cm RMS level. Over the last year we have focused on improving the quality of the single-frequency, GPS-based orbits. In the subsequent sections we will describe our approaches for improving these orbits. Currently, we can produce single-frequency, GPS-based orbits for T/P with radial accuracies better than 3 cm RMS.

The Geosat Follow-On (GFO) mission is sponsored by the US Navy and is the latest spaceborne radar altimetric mission. The GFO satellite was launched on February 10, 1998, and carries four 8-channel, codeless TurboRogue GPS receivers (1 active and 3 spares). These receivers should permit tracking of both L1 and L2 data, independent of AS status. Orbits at the 2-3 cm RMS level are expected with the dual-frequency data. At this writing, one of the receivers is switched on, but is not being utilized yet operationally due to lower than expected SNR levels. JPL engineers are working with the contractor that integrated the receivers on the spacecraft to diagnose the problem.

NEAR REAL-TIME USE OF T/P ALTIMETER MEASUREMENTS

In the introduction we pointed out that the usefulness of satellite altimetric data hinges on the availability of high-quality orbits for the satellite. For T/P the definitive orbit is the NASA Precise Orbit Ephemeris (POE) [Marshall et al., 1995]. The POE is generated using DORIS and SLR data and is generally accepted to be radially accurate to about 2 cm RMS [cf., Tapley and Ries, 1997]. However, the latency period between the end of data collection and the release of the POE is over 1 month, in part because the solution goes through extensive validation prior to its release. This precludes the use of altimeter measurements, with the definitive T/P orbit, in any near real-time applications.

Fortunately, the single-frequency, GPS-based orbits for T/P are at a level of accuracy that permits their use with altimeter data in many operational applications. For example, the GPS-based orbits permit the near real-time assimilation of the T/P altimeter data in a coupled ocean-atmosphere model at NOAA's National Center for Environmental Prediction (NCEP) [cf., Cheney et al., 1997]. Output from this operational forecast model played a major role in the NCEP's Spring 1997 decision to issue a forecast for the current El Niño event. (As of early May 1998, some of the effects of this El Niño event were still evident in the Pacific.) Moreover, the availability of accurate altimetric data, on a near real-time basis, permitted the near real-time monitoring of the El Niño event.

Clearly, emerging operational operations that use altimeter data with near real-time orbits will benefit greatly from having the most accurate orbits available. Over the last twelve months, the single-frequency, GPS-based orbits produced by JPL for T/P have substantially improved in quality. Currently we can produce T/P orbits on a next-day basis which are radially accurate to better than 3 cm RMS. This level of accuracy is unprecedented for single-frequency, GPS-based orbits and almost approaches the level of accuracy of the definitive T/P orbit.

SOFTWARE FOR GPS-BASED T/P ORBIT PRODUCTION: GOA II

Our GPS-based orbits for T/P are computed using JPL's GIPSY OASIS II (GOA II) software suite [cf., Webb et al., 1993]. GOA II is a collection of FORTRAN programs and encapsulating scripts. (The scripts are either C-shell scripts or Perl scripts, which facilitate the automation of routine computing tasks.) Communication between the various modules in the software suite is via well-defined input and output files.

GOA II has been used extensively at JPL, and elsewhere, for precision orbit determination of both GPS and other satellites. It has also been used for precise geodetic applications, such as estimation of plate motion and crustal deformation through precise point-positioning of GPS receivers.

The GPS-based orbit for T/P is generated using an automated process which calls the various modules in GOA II [cf., Muellerschoen et al., 1995]. This script runs on a daily basis; it wakes every 30 minutes and interrogates our databases to see what data is available to generate an orbit. When sufficient data are available, an orbit spanning a 27 hour arc (24 hours plus last 3 hours from previous day) is computed. The automated process performs several internal checks to gauge the quality of the computed orbit (such as computing postfit residuals or differences in the 3 hour overlap period with the previous day's solution). Based on a sequence of (overlapping) 27-hour arc solutions, a solution spanning a 10-day repeat cycle can be generated by merging the 10 daily solutions using a cosine taper. (The exact ground-track repeat cycle for T/P is 9.915625 days and is commonly referred to as the "10-day" T/P repeat cycle.) This provides us with an orbit which can be compared with the NASA POE.

ORBIT IMPROVEMENT FOR T/P

Modeling the ionosphere delay: As we already pointed out, when AS is off the GPSDR can track both L1 and L2 signals. Linearly combining the corresponding data permits the leading order effects of the ionosphere to be removed from range measurements. When AS is on, only the L1 signal is tracked and the effects of the ionosphere must be modeled. Until June, 1997, the Bent ionosphere model [cf., Bent et al, 1976] was used for computing the ionosphere delay in our near real-time processing. This is a climatological model and is constructed, by a fit to empirical measurements, to yield an average response for the ionosphere. With the Bent model the radial accuracy of the next-day, GPS-based orbits was about 6 cm RMS. In June, 1997, we switched to modeling the ionosphere

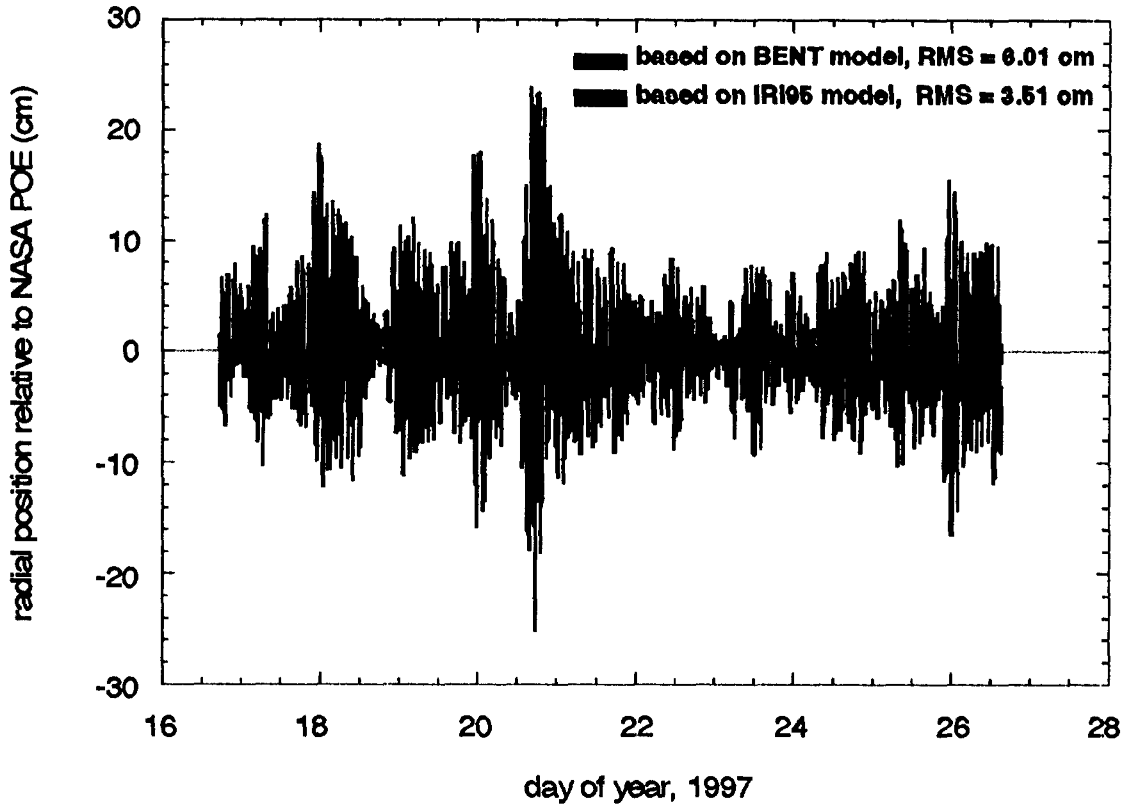

Figure 1: Cycle 160 radial position of GPOEs, computed using Bent and IRI95 ionosphere models, relative to the definitive T/P orbit (the NASA POE).

delay using another climatological model, the IRI95 ionosphere model [cf., Bilitza et al., 1993]. To illustrate the improvement in orbit quality, we compare two GPS-based orbits (one computed with the Bent model, the other with IRI95) for repeat cycle 160 with the definitive T/P orbit, i.e., the NASA POE. (Repeat cycle 160 is the 160-th "10-day" repeat cycle of T/P and is from January 16, 1997, to January 26, 1997.) In Figure 1, we depict the radial difference of the two GPS-based POEs (GPOEs) relative to the NASA POE. Clearly, the orbit based on the IRI95 ionosphere model is in much closer agreement with the definitive orbit.

Another means of assessing the radial orbit accuracy is provided by comparing altimeter-derived sea-surface heights at ground-track intersections. These intersections occur whenever an ascending and a descending segment of the satellite orbit pass over the same point on the Earth's surface. After correcting the altimeter measurements for effects such as ocean tides, sea-state, pressure-loading and so on, their difference provides us with a valuable metric of the radial orbit error. Other altimetric error sources as well as oceanographic effects (e.g., changes in currents), contribute to the height misclosure at a crossover location. We attempt to minimize these effects by "super-editing" the crossover residuals according to certain geophysical and environmental criteria, and by restricting the comparison to crossovers occurring within a single "10-day" repeat cycle.

In Figure 2(a) we plot the cycle 160 crossovers for the GPOE computed using the Bent ionosphere model, in Figure 2(b) we plot the crossovers for the GPOE computed using the IRI95 ionosphere model and in Figure 2(c) we plot the crossovers for the NASA POE. Figure 2(c) depicts the ideal histogram profile: tall and narrow. Comparing the histograms for the GPOEs, we see that the profile for the orbit based on IRI95 is closer to the ideal shape. This is also reflected in the RMS of the crossover

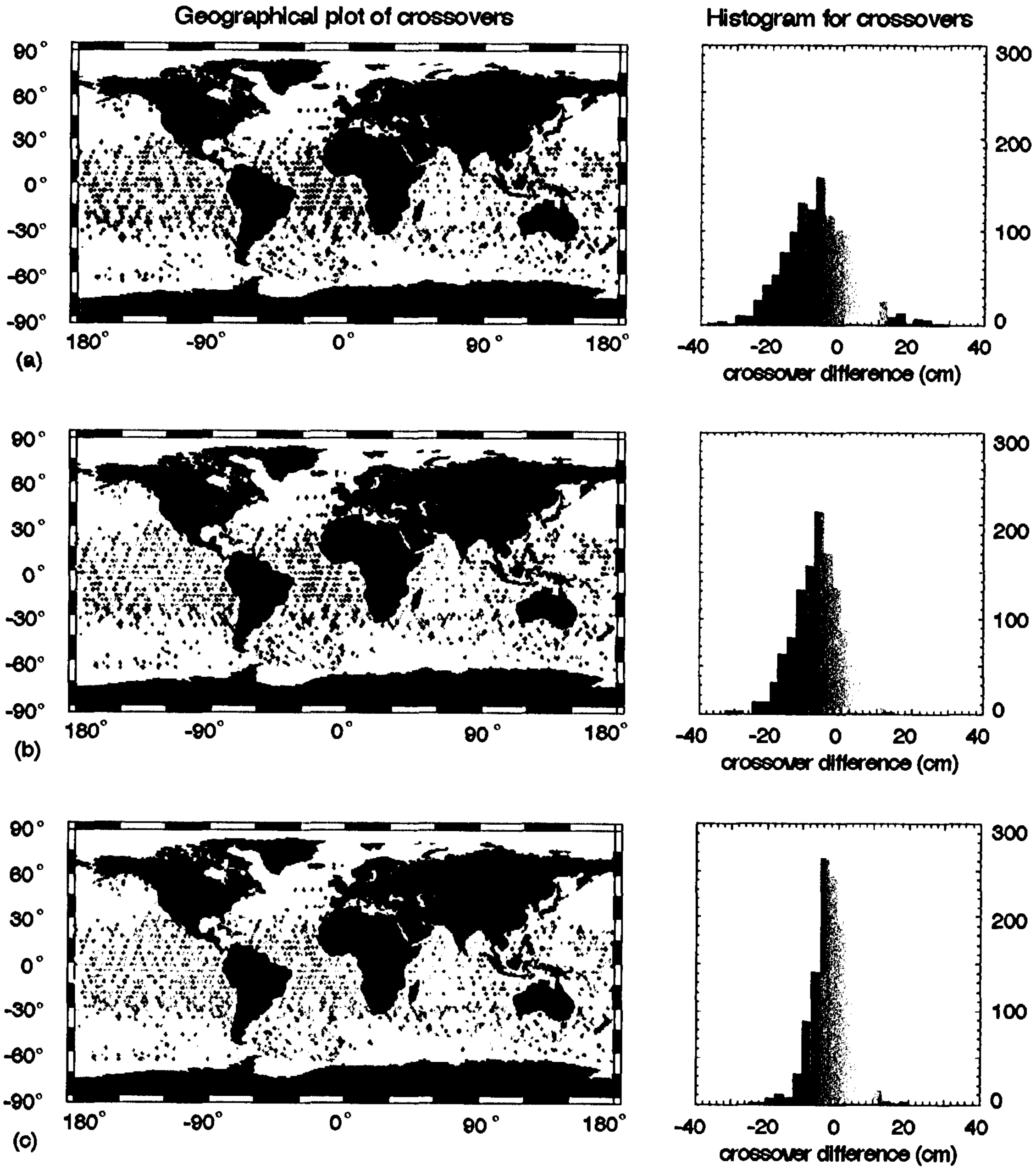

Figure 2: Cycle 160 super-edited crossover differences: (a) GPOE computed with Bent ionosphere model, RMS of the crossover differences is 11.64 cm; (b) GPOE computed with IRI95 ionosphere model, RMS of the crossover differences is 7.97 cm; (c) NASA POE, RMS of the crossover differences is 5.44 cm.

differences, which improves from 11.64 cm for the Bent model to 7.97 cm for the IRI95 model. From analysis of the crossover statistics for a sequence of cycles, we infer that radial orbit accuracy improves from about 6.2 cm RMS with the Bent model to about 4.3 cm RMS with the IRI95 model.

In what follows we will build on these improvements by continuing to use the IRI95 ionosphere model. Moreover, we will illustrate our improved orbits using only the altimeter crossovers. Since the definitive orbit (POE) is radially accurate to only the 2 cm level, it may be misleading to look at radial differences relative to the definitive orbit. When trying to identify small orbit changes, radial differences relative to the definitive orbit may indicate GPOE improvement where there is none, or vice versa. On the other hand, changes in altimeter crossover differences can be directly correlated with changes in orbit quality.

Interfrequency bias estimates and group delay differentials for GPS satellites: On account of the physical separation between the frequency source and the antenna phase center on GPS satellites, there is a resulting frequency-dependent time-lag between GPS signal generation and broadcast. If for GPS satellite X, $T_{L1,X}$ is the time-lag for the L1 signal and $T_{L2,X}$ is the time-lag for the L2 signal then we have the following relationship between the two [cf., section 20.3.3.3.3.2 of the GPS interface control document ICD-GPS-200C]:

$$T_{L2,X} = (f_{L1} / f_{L2})^2\, T_{L1,X}$$

where f_{L1} and f_{L2} are the L1 and L2 frequencies. If we use only L1 data along with exact GPS clocks, and fail to account for the $T_{L1,X}$ time-lag, then pseudoranges between T/P and GPS satellite X will contain an unknown bias [cf., van Dierendonck et al., 1980]. Values for each $T_{L1,X}$, are contained in the current broadcast navigation message and are referred to as group delay differentials. However, these values are based on prelaunch measurements and are not generally reliable for precise applications. Fortunately, the JPL project for computing near real-time maps of the ionosphere [cf., Manucci et al., 1993; and Manucci et al., 1995] provides us with reliable estimates of related quantities: the interfrequency biases. For GPS satellite X, the interfrequency bias $T_{IF,X}$ is simply the difference between the L1 and L2 time-lags, i.e.,

$$\begin{aligned} T_{IF,X} &= T_{L1,X} - T_{L2,X} \\ &= ((f_{L2}^2 - f_{L1}^2) / f_{L2}^2)\, T_{L1,X} \end{aligned}$$

which implies that estimates of $T_{IF,X}$ allow us to compute estimates of $T_{L1,X}$. Using the values for the $T_{L1,X}$ time-lags based on the interfrequency bias estimates leads to reduced postfit pseudorange residuals (from about 90 cm to about 45 cm) and improved orbits. The RMS of the crossovers for cycle 160 is suggestive of a very slight degradation in accuracy. The crossovers for the cycle 160 GPOE computed using the interfrequency bias estimates are depicted in Figure 3. However, analysis of a sequence of cycles indicates that the radial orbit accuracy improves to about 3.6 cm RMS, when interfrequency bias estimates are used.

Dynamic modeling errors: When AS was off, prior to January 1994, errors in the T/P orbit from unmodeled or mismodeled forces could be significantly reduced by estimating certain stochastic acceleration parameters in a so-called reduced dynamic filter pass [cf., Bertiger et al., 1994]. When AS was activated, systematic measurement model errors, principally due to the mismodeled ionosphere delay, contaminated the tracking observations to such a degree that reduced dynamic filtering was no longer feasible. Now, however, errors from mismodeling the ionosphere have been substantially reduced, making it possible to attempt a limited type of reduced dynamic filtering. The unmodeled and mismodeled forces are resonant at a frequency of

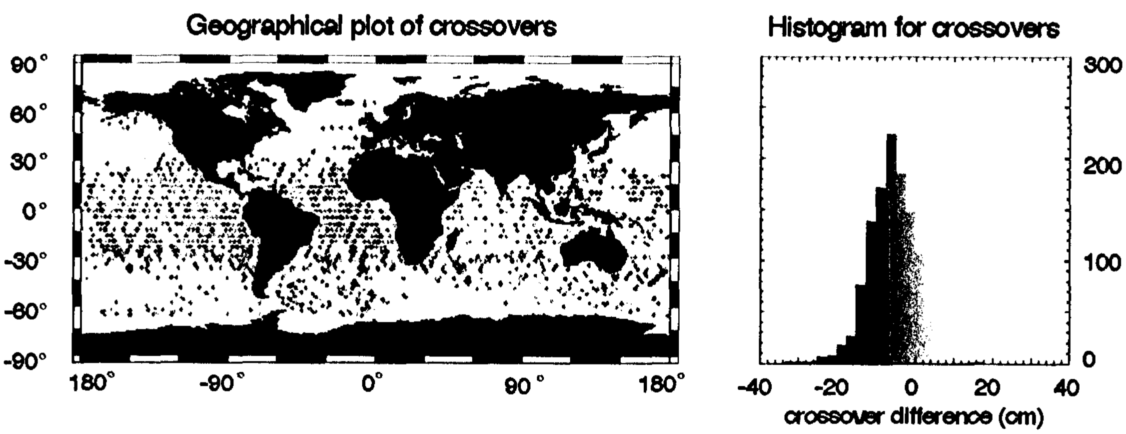

Figure 3: Cycle 160 super-edited crossover differences for GPOE computed using interfrequency bias estimates; RMS of the crossover differences is 8.29 cm.

	dual-frequency strategy	single-frequency strategy
parameters	constant radial, cross-track & down-track	constant down-track; sine & cosine 1/rev in down-track and cross-track
type	colored noise; correlation times of 15 minutes	colored noise; correlation times of 6 hours
steady state σ's	10 nm/s^2 radial; 20 nm/s^2 cross-track & down-track	0.5 nm/s^2 constant down-track; 1.0 nm/s^2 others
carrier phase data weights	2 cm in d.f.p. 1 cm in r.d.f.p.	20 cm in d.f.p. 5 cm in r.d.f.p.
pseudorange data weights	300 cm in d.f.p. 300 cm in r.d.f.p.	80 cm in d.f.p. 40 cm in r.d.f.p.

Table 1: Comparison of reduced dynamic filter strategies for dual-frequency data and single-frequency data. Note: d.f.p. indicates "dynamic filter pass" and r.d.f.p. indicates "reduced dynamic filter pass.

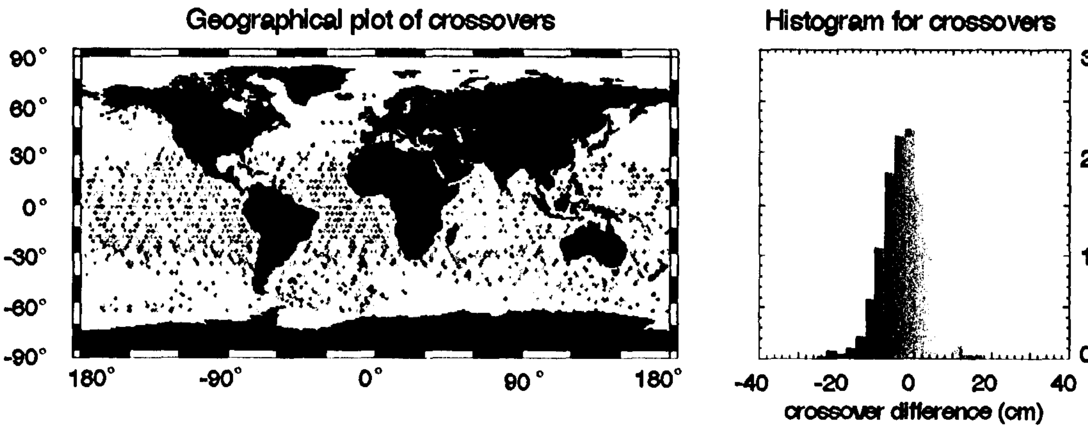

Figure 4: Cycle 160 super-edited crossover differences for GPOE computed using single-frequency reduced dynamic filtering strategy; RMS of the crossover differences is 6.18 cm.

once-per-revolution (1/rev). Consequently, it makes sense to estimate acceleration parameters that have the same frequency. In fact, in our regular solution strategy we estimate such acceleration parameters, but the corresponding harmonic 1/rev coefficients are treated as constant throughout the solution arc. With our reduced dynamic filter, the estimated acceleration parameters are allowed to modulate, with a new estimate being generated for every hour of the solution arc. In Table 1 we compare the reduced dynamic filtering strategy for both dual-frequency (AS-off) data and single-frequency (AS-on) data. It should be noted that the estimated acceleration parameters for the single-frequency strategy will be quite small (steady-state σ's are an order of magnitude smaller than in the dual-frequency strategy), preventing the reduced dynamic solution from deviating very far from the solution generated with our regular strategy (dynamic filtering). In Figure 4 we depict the cycle 160 crossovers for the GPOE computed using the single-frequency reduced dynamic filtering strategy. This compares very favorably with the crossover plots in Figure 2(c) for the NASA POE. Analysis of a sequence of cycles indicates that the radial accuracy improves to about 2.6 cm RMS when we use the single-frequency reduced dynamic filtering strategy.

Synopsis of improvements: In the previous subsections, we quoted radial error measurements, for the different solution

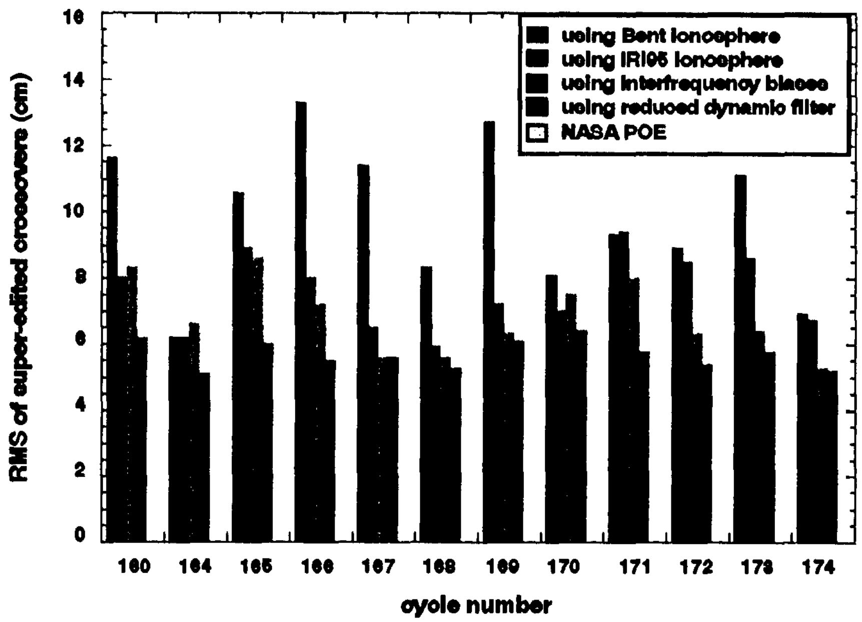

Figure 5: Comparison of RMS of super-edited crossover differences for a sequence of repeat cycles, indicating improvements in GPOE accuracy for the different solution strategies outlined in the main text. The RMS of the crossover differences for the NASA POE are also depicted for comparison.

strategies, that were based on a sequence of repeat cycles. The cycles chosen were 160 and 164 through 174. In Figure 5 we depict the RMS of the crossover differences, for each repeat cycle and for each solution strategy. For comparison, the RMS of the crossover differences for the NASA POE are also depicted. Assuming the NASA POE is radially accurate to about 2 cm RMS, we can estimate the radial accuracies of the different GPOEs, which are presented in Table 2. From Table 2 and Figure 5, it is clear that single-frequency GPS-based orbits for T/P can now be produced, on a next-day basis, which have radial accuracies better than 3 cm RMS.

strategy	radial RMS accuracy
Bent Ionosphere	6.2 cm
IRI95 Ionosphere	4.3 cm
Interfrequency biases	3.6 cm
reduced dynamic filter	2.6 cm

Table 2: comparison of the radial RMS accuracies for the different solution strategies.

SUMMARY AND CONCLUSIONS

We have shown how availability of near real-time orbits permit the use of T/P altimeter data in emerging operational applications. In addition, we have shown that the next-day, single-frequency, GPS-based orbits for T/P can now be produced with an accuracy level that approaches that of the definitive T/P orbit (i.e., the NASA POE). This means that near real-time monitoring of our oceans can now be performed with an unprecedented level of accuracy.

It is also possible that further gains in accuracy can be realized by using a data driven ionosphere map, such as the near real-time global ionosphere maps produced at JPL [cf., Manucci et al., 1993]. Whenever there is a dynamic ionosphere (i.e., whenever there is an ionospheric storm) these maps are far superior when compared to the climatological models.

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